

## DESCRIPTION

3D IMAGE DISPLAY APPARATUS AND 3D IMAGE DISPLAY METHOD**Technical Field**

[0001] The present invention relates to an apparatus and a method for making illumination light components of multiple wavelengths incident to a hologram, thereby generating reproduced light components of the wavelengths from the hologram, and displaying a 3D image based on these reproduced light components.

**Background Art**

[0002] A 3D image display apparatus making use of a hologram is configured to generate a reproduced light component from a hologram under illumination with an illumination light component and to display a 3D image from the reproduced light component thus generated. Another 3D image display apparatus is configured to make illumination light components of multiple wavelengths (e.g., three-color components of red, green, and blue) incident to a hologram, thereby enabling color display of a 3D image.

[0003] A first conventional technology known heretofore is a technology of making use of a photographic plate permitting high-resolution recording. In this first conventional technology, hologram recording is carried out by making reference

light components and object light components of  
respective wavelengths incident to a photographic plate  
and thereby multiply recording holograms associated  
with the respective wavelengths on the photographic  
5 plate. On the other hand, reproduction is implemented  
by making illumination light components of the same  
wavelengths as those in the recording, incident from an  
identical incident direction to the holograms to  
generate reproduced light components of the  
10 wavelengths. This results in superimposing images of  
these reproduced light components on each other at the  
same position, thereby obtaining a color 3D image.

[0004] However, since in this first conventional  
technology the holograms associated with the respective  
15 wavelengths are multiply recorded on the photographic  
plate, the illumination light component of a wavelength  
 $\lambda_a$  is incident to the hologram associated with the  
wavelength  $\lambda_a$  to generate the reproduced light  
component of the wavelength  $\lambda_a$ , and the illumination  
20 light component of another wavelength  $\lambda_b$  ( $\lambda_a \neq \lambda_b$ ) is  
also incident to the hologram associated with the  
wavelength  $\lambda_a$  to generate a reproduced light component  
of the wavelength  $\lambda_b$  from the hologram associated with  
the wavelength  $\lambda_a$  as well. Among these reproduced  
25 light component of wavelength  $\lambda_a$  and reproduced light  
component of wavelength  $\lambda_b$ , the reproduced light

component of wavelength  $\lambda_a$  is the light component necessary for color display of the original 3D image. In contrast to it, the reproduced light component of wavelength  $\lambda_b$  is a light component reproduced at a different position and at a different magnification from those of the original 3D image, and is thus a crosstalk component against the original 3D image to hinder display of the 3D image. In order to avoid such crosstalk, therefore, recording is carried out by making the reference light components of multiple wavelengths incident from mutually different directions to the photographic plate where the object light components are incident approximately normally to the photographic plate, whereby crosstalk light components are prevented from being superimposed on the original 3D image in the reproduction.

[0005] As a second conventional technology, Kunihiro Takano et al. "Study of color holography 3D television with white light," Proceedings of 3D Image Conference 2000, pp179-182 discloses a technology of making use of three types of spatial light modulators capable of presenting a hologram. Specifically, a first spatial light modulator presents a hologram associated with red light, a second spatial light modulator a hologram associated with green light, and a third spatial light modulator a hologram associated

with blue light. Then a red illumination light component is made incident to the first spatial light modulator, a green illumination light component to the second spatial light modulator, and a blue illumination light component to the third spatial light modulator, whereby reproduced light components generated from the respective spatial light modulators are spatially superimposed, and zero-order transmitted light is removed by a mask disposed in a subsequent stage, thereby obtaining a color 3D image.

[0006] Furthermore, a third conventional technology is the technology described in Japanese Patent Application Laid-Open No. 2000-250387, which positively makes use of the pixel structure of the spatial light modulator being discrete. Specifically, when parallel light is made incident into an ordinary diffraction grating, there appear not only a zero-order diffracted wave but also first and higher-order diffracted waves. Likewise, reproduced light components generated from a spatial light modulator having the discrete pixel structure also include a zero-order diffracted wave and higher-order diffracted waves. Concerning two adjacent pixels in a spatial light modulator, where a presentation range is limited to a range in which phase differences between synthetic wavefronts of an object light component and a reference

light component are less than  $\pi$  (i.e., a range without alias components) and where a hologram is presented on the spatial light modulator, wavefronts of higher-order diffracted waves of reproduced light components generated from the spatial light modulator upon incidence of the illumination light component coincide with those of the zero-order diffracted waves. However, directions of emergence from the spatial light modulator are different among orders. The reproduced light components undergo wavefront transformation to be separated at intervals of  $\lambda f/P$  in each order of the diffracted waves on the rear focal plane of a lens provided behind the spatial light modulator. Here  $\lambda$  is the wavelength of the illumination light component,  $f$  the focal length of the lens, and  $P$  the pixel pitch of the spatial light modulator. Therefore, a desired 3D image is obtained in a manner of disposing a mask with an aperture of rectangular shape having the length of  $\lambda f/P$  on each side on the rear focal plane of the lens and letting the zero-order diffracted wave of the reproduced light components pass through this aperture. The higher-order diffracted waves are blocked by this mask on the other hand.

[0007] In the above third conventional technology, concerning two adjacent pixels in the spatial light modulator, where the presentation range is limited to a

range in which phase differences between synthetic wavefronts of an object light component and a reference light component are not less than  $\pi$  and are less than  $2\pi$  (i.e., a range including a first-order alias component) and where a hologram is presented on the spatial light modulator, the wavefronts of the higher-order diffracted waves of the reproduced light components generated from the spatial light modulator upon incidence of the illumination light component coincide with the zero-order diffracted wave. For this reason, the zero-order diffracted wave and all the higher-order diffracted waves include their first-order alias component. Only a desired first-order diffracted wave among the reproduced light components can be extracted in a manner of disposing a mask with an aperture of rectangular shape having the length of  $\lambda f/P$  on each side on the rear focal plane of the lens disposed behind the spatial light modulator and letting the first-order diffracted wave of the reproduced light components pass through this aperture. The zero-order diffracted wave and the second and higher-order diffracted waves are blocked by the mask on the other hand.

Namely, the above third conventional technology is to present the hologram on the spatial light modulator while limiting the presentation range to the

range including the alias component of a specific order and to extract the diffracted wave of the specific order out of the reproduced light components by use of the mask with the aperture at the position corresponding to the specific order. The presentation of the hologram and the selection of the aperture associated with each order are implemented based on time-sharing or spatial synthesis, thereby enabling expansion of the emergence direction range of the reproduced image (i.e., a viewing area) formed by the lens.

#### **Disclosure of the Invention**

[0008] Inventors studied each of the aforementioned first to third conventional technologies and found the following problems. Namely, the first conventional technology is suitable for cases making use of the photographic plate capable of high-resolution recording. With use of a spatial light modulator having a low spatial resolution, however, it does not allow setting of a large angle of incidence of the illumination light component to the spatial light modulator, so that the reproduced light components serving as crosstalk upon reproduction are superimposed on the original 3D image. As discussed in the description of the third conventional technology, there occurs superposition of diffracted waves of respective

orders generated from the spatial light modulator having the discrete pixel structure. In this respect, it is difficult to apply the foregoing first conventional technology to the spatial light modulator having the discrete pixel structure and low resolution.

[0009] The second conventional technology involves the spatial superposition of reproduced light components generated from the respective spatial light modulators, but requires a half mirror for the superposition. For this reason, the second conventional technology brings about an increase in the scale of apparatus and a reduction in the light quantity of the reproduced light components. In order to compensate for the reduction in the light quantity of the reproduced light components, the second conventional technology requires laser light sources for outputting laser light of high power as the illumination light components, or a dielectric mirror having wavelength selectivity, which makes the apparatus itself expensive.

[0010] The third conventional technology is directed toward the objective of expansion of the viewing area and the illumination light component of a single wavelength is made incident normally to the spatial light modulator. Therefore, this third conventional technology is neither a technology of



making illumination light components of multiple wavelengths incident to a spatial light modulator, nor a technology of making an illumination light component obliquely incident to the spatial light modulator. The  
5 third conventional technology has a problem of increase in the scale of the apparatus itself due to the spatial synthesis and a problem of increase in the cost of the apparatus itself due to the necessity for provision of a high-speed shutter on the rear focal plane of the  
10 lens for time-sharing.

[0011] The present invention has been accomplished in order to solve the problems as described above, and an object of the invention is to provide a compact and inexpensive 3D image display apparatus and a 3D image  
15 display method capable of presenting color display of a clear 3D image even with use of a spatial light modulator of a low resolution.

[0012] A 3D image display apparatus according to the present invention is an apparatus for making  
20 illumination light components of multiple wavelengths incident to a hologram, thereby generating reproduced light components of the wavelengths from the hologram, and displaying a 3D image based on these reproduced light components. Specifically, the 3D image display  
25 apparatus according to the present invention comprises a spatial light modulator, an illumination optical

system, a reproduced image transforming optical system,  
and a mask. The spatial light modulator has a discrete  
pixel structure to present holograms associated with  
the respective wavelengths. The illumination optical  
5 system converts each of the illumination light  
components of the wavelengths into a parallel plane  
wave, and makes the parallel plane waves incident from  
mutually different incident directions to the spatial  
light modulator. The reproduced image transforming  
10 optical system subjects each of reproduced images of  
the wavelengths generated from the holograms presented  
on the spatial light modulator, to wavefront  
transformation into a virtual image or a real image.  
The mask has an aperture provided on a focal plane of  
15 the reproduced image transforming optical system.  
Particularly, in the 3D image display apparatus  
according to the present invention, the illumination  
optical system sets the incident directions of the  
respective illumination light components of the  
20 wavelengths to the spatial light modulator so that  
diffracted waves of any order out of the reproduced  
light components of the wavelengths are superimposed on  
each other in the aperture after the wavefront  
transformation by the reproduced image transforming  
25 optical system.

[0013] A 3D image display method according to the

present invention is a method of making illumination light components of multiple wavelengths incident to a hologram, thereby generating reproduced light components of the wavelengths from the hologram, and displaying a 3D image based on these reproduced light components. Specifically, the method comprises preparing a spatial light modulator having a discrete pixel structure for presenting holograms associated with the respective wavelengths, letting an illumination optical system convert each of the illumination light components of the wavelengths into a parallel plane wave and make the parallel plane waves incident from mutually different incident directions to the spatial light modulator, letting a reproduced image transforming optical system subject each of reproduced images of the wavelengths generated from the holograms presented on the spatial light modulator, to wavefront transformation into a virtual image or a real image, placing a mask with an aperture on a focal plane of the reproduced image transforming optical system, and letting the illumination optical system set the incident directions of the respective illumination light components of the wavelengths to the spatial light modulator so that diffracted waves of any order out of the reproduced light components of the wavelengths are superimposed on each other in the

aperture after the wavefront transformation by the reproduced image transforming optical system.

[0014] According to the present invention, the holograms associated with the respective wavelengths

5 are presented on the spatial light modulator having the

discrete pixel structure. The illumination optical system converts each of the illumination light components of the wavelengths into a parallel plane

wave and makes the parallel plane waves incident from

10 the mutually different incident directions to this

spatial light modulator. Each of the reproduced images

of the wavelengths generated from the holograms

presented on the spatial light modulator is subjected

to the wavefront transformation by the reproduced image

15 transforming optical system into a virtual image or a

real image. The mask with the aperture is disposed on

the focal plane of the reproduced image transforming

optical system. Then the incident directions of the

respective illumination light components of the

20 wavelengths to the spatial light modulator are set by

the illumination optical system so that the diffracted

waves of any order out of the reproduced light

components of the wavelengths are superimposed on each

other in the aperture after the wavefront

25 transformation by the reproduced image transforming

optical system.

[0015] In the 3D image display apparatus or the 3D image display method according to the present invention, the illumination optical system preferably comprises a plurality of monochromatic light sources having their respective output wavelengths different from each other, a plurality of pinholes disposed in proximity to the respective monochromatic light sources, and a collimating optical system for collimating light having been emitted from the respective monochromatic light sources and having passed through the pinholes.

[0016] In the 3D image display apparatus or the 3D image display method according to the present invention, the illumination optical system preferably comprises an achromatic lens having an identical focal length for the light components of the wavelengths, and the reproduced image transforming optical system preferably comprises an achromatic lens having an identical focal length for the light components of the wavelengths.

[0017] In the 3D image display apparatus or the 3D image display method according to the present invention, more preferably, the incident directions of the respective illumination light components of the wavelengths to the spatial light modulator are set by the illumination optical system so that zero-order

5        diffracted waves of the respective reproduced light components of the wavelengths are superimposed on each other in the aperture after the wavefront transformation by the reproduced image transforming optical system.

10        [0018]        In the 3D image display apparatus or the 3D image display method according to the present invention, the incident directions of the respective illumination light components of the wavelengths to the spatial light modulator may be so set by the illumination optical system that an illumination light component of any one specific wavelength out of the wavelengths is normally incident to the spatial light modulator and that a zero-order diffracted wave of a reproduced light component of the specific wavelength and a higher-order diffracted wave of a reproduced light component of another wavelength are superimposed on each other in the aperture after the wavefront transformation by the reproduced image transforming optical system.

20        [0019]        In the 3D image display apparatus or the 3D image display method according to the present invention, where  $P$  represents a pixel pitch of the spatial light modulator,  $f$  a focal length of the reproduced image transforming optical system,  $n_1$  an order of a diffracted wave of a reproduced light

component of a shortest wavelength  $\lambda_1$  out of the wavelengths, and  $n_i$  an order of a diffracted wave of a reproduced light component of another wavelength  $\lambda_i$ , an incidence angle  $\theta_i$  of an illumination light component of the wavelength  $\lambda_i$  to the spatial light modulator is expressed by an equation below:

[0020] 
$$\theta_i = \sin^{-1}\{(n_1\lambda_1 - n_i\lambda_i)/P\}, \text{ and}$$

the aperture is preferably of a rectangular shape having a length of not more than  $\lambda_1 f/P$  on each side.

[0021] In the 3D image display apparatus or the 3D image display method according to the present invention, preferably, the spatial light modulator has a transmission type structure in which the reproduced light components are emitted on the side opposite to the side where the illumination light components are incident, or a reflection type structure in which the reproduced light components are emitted on the same side as the side where the illumination light components are incident. In a case where the spatial light modulator has the reflection type structure, the illumination optical system and the reproduced image transforming optical system preferably share one or more optical components.

[0022] In the 3D image display apparatus or the 3D image display method according to the present invention, the spatial light modulator may be provided

with microlenses for respective pixels.

[0023] Each of embodiments of the present invention will become more fully understandable in view of the detailed description and accompanying drawings which will follow. It is noted that these embodiments are presented merely for illustrative purposes only but are not to be construed in a way of limiting the invention.

[0024] The range of further application of the present invention will become apparent in view of the following detailed description. However, the detailed description and specific examples will describe the preferred embodiments of the present invention, but it is apparent that they are presented for illustrative purposes only and that various modifications and improvements falling within the spirit and scope of the present invention are obvious to those skilled in the art in view of the detailed description.

#### **Brief Description of the Drawings**

[0025] Fig. 1 is an illustration showing a configuration of a first embodiment of the 3D image display apparatus according to the present invention;

[0026] Fig. 2 is an illustration for explaining an illumination optical system and a spatial light modulator of the 3D image display apparatus according to the first embodiment;



[0027] Fig. 3 is an illustration for explaining the illumination optical system of the 3D image display apparatus according to the first embodiment;

[0028] Fig. 4 is an illustration for explaining a display operation of a luminescent point in a 3D image in a case where a blue illumination light component is normally incident to the spatial light modulator, in the 3D image display apparatus according to the first embodiment;

[0029] Fig. 5 is an illustration for explaining a hologram presented on the spatial light modulator when the blue illumination light component is normally incident to the spatial light modulator, in the 3D image display apparatus according to the first embodiment;

[0030] Fig. 6 is an illustration for explaining a display operation of a luminescent point in a 3D image in a case where an illumination light component is obliquely incident to the spatial light modulator, in the 3D image display apparatus according to the first embodiment;

[0031] Fig. 7 and Fig. 8 are illustrations for explaining holograms prepared by a first hologram preparing method;

[0032] Fig. 9 is an illustration for explaining a display operation of a luminescent point in a 3D image

in a case where an illumination light component is obliquely incident to the spatial light modulator while the hologram shown in Fig. 7 is presented on the spatial light modulator;

5       [0033]       Fig. 10 is an illustration for explaining a second hologram preparing method;

[0034]       Fig. 11 is an illustration showing arrangement of point light sources of three wavelengths in an ideal case;

10       [0035]       Fig. 12 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a red reproduced light component at the mask position, in the ideal case;

15       [0036]       Fig. 13 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a green reproduced light component at the mask position, in the ideal case;

20       [0037]       Fig. 14 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a blue reproduced light component at the mask position, in the ideal case;

25       [0038]       Fig. 15 is an illustration showing the wavefront transformation areas of zero-order diffracted waves of respective reproduced light components of red, green, and blue at the mask position, in the ideal case;

[0039] Fig. 16 is an illustration showing arrangement of three point light sources in an illumination light source section 10 of the 3D image display apparatus according to the first embodiment;

5 [0040] Fig. 17 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a red reproduced light component at the mask location in the 3D image display apparatus according to the first embodiment;

10 [0041] Fig. 18 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a green reproduced light component at the mask location in the 3D image display apparatus according to the first embodiment;

15 [0042] Fig. 19 is an illustration showing wavefront transformation areas of zero-order diffracted waves of respective reproduced light components of red, green, and blue at the mask location in the 3D image display apparatus according to the first embodiment;

20 [0043] Fig. 20 is an illustration showing arrangement of three point light sources in an illumination light source section in modification example A of the 3D image display apparatus according to the first embodiment;

25 [0044] Fig. 21 is an illustration showing a wavefront transformation area of a zero-order

diffracted wave of a red reproduced light component at the mask location, in modification example A of the 3D image display apparatus according to the first embodiment;

5 [0045] Fig. 22 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a green reproduced light component at the mask location, in modification example A of the 3D image display apparatus according to the first  
10 embodiment;

[0046] Fig. 23 is an illustration showing wavefront transformation areas of zero-order diffracted waves of respective reproduced light components of red, green, and blue at the mask location, in modification  
15 example A of the 3D image display apparatus according to the first embodiment;

[0047] Fig. 24 is an illustration showing arrangement of three point light sources in an illumination light source section in modification  
20 example B of the 3D image display apparatus according to the first embodiment;

[0048] Fig. 25 is an illustration showing a wavefront transformation area of a zero-order diffracted wave of a green reproduced light component  
25 at the mask location, in modification example B of the 3D image display apparatus according to the first

embodiment;

[0049] Fig. 26 is an illustration showing wavefront transformation areas of zero-order diffracted waves of respective reproduced light components of red, green, and blue at the mask location, in modification example B of the 3D image display apparatus according to the first embodiment;

[0050] Fig. 27 is an illustration showing a configuration of a second embodiment of the 3D image display apparatus according to the present invention;

[0051] Fig. 28 is an illustration showing a configuration of a third embodiment of the 3D image display apparatus according to the present invention;

[0052] Fig. 29 is an illustration showing wavefront transformation areas of zero-order diffracted waves of respective reproduced light components of red, green, and blue at the mask location in the 3D image display apparatus according to the third embodiment;

[0053] Fig. 30 is an illustration showing a configuration of a fourth embodiment of the 3D image display apparatus according to the present invention;

[0054] Fig. 31 and Fig. 32 are illustrations showing wavefront transformation areas of diffracted waves of each order of respective reproduced light components of red, green, and blue at the mask location in the 3D image display apparatus according to the

fourth embodiment;

[0055] Fig. 33 is an illustration for explaining a spatial light modulator and a wavefront transforming optical system in the 3D image display apparatus according to the fourth embodiment;

[0056] Fig. 34 is an illustration for explaining a relation between an angle of incidence of an illumination light component and an angle of emergence of a reproduced light component in the spatial light modulator of the 3D image display apparatus according to the fourth embodiment;

[0057] Fig. 35 is an illustration showing a configuration of a fifth embodiment of the 3D image display apparatus according to the present invention; and

[0058] Fig. 36 is an illustration showing a configuration of a sixth embodiment of the 3D image display apparatus according to the present invention.

#### **Best Mode for Carrying out the Invention**

[0059] Each of embodiments of the 3D image display apparatus and 3D image display method according to the present invention will be described below in detail with reference to Figs. 1-4 to Fig. 36. Identical or equivalent elements will be denoted by the same reference symbols in the description of the drawings, without redundant description. For convenience' sake

of description, a coordinate system in each drawing is the xyz orthogonal coordinate system in which the z-axis is defined along a direction normal to the spatial light modulator.

5 (First Embodiment)

[0060] First, the first embodiment of the 3D image display apparatus and 3D image display method according to the present invention will be described. Fig. 1 is an illustration showing a configuration of the first  
10 embodiment of the 3D image display apparatus according to the present invention. The 3D image display apparatus 1 shown in this figure has an illumination light source section 10, a lens 20, a spatial light modulator 30 of the transmission type, a lens 40, and a  
15 mask 50. The illumination light source section 10 and the lens 20 constitute an illumination optical system for converting each of illumination light components of three wavelengths into a parallel plane wave and making the parallel plane waves incident from mutually  
20 different incident directions to the spatial light modulator 30. The lens 40 constitutes a reproduced image transforming optical system for subjecting each of reproduced images of the three wavelengths generated from holograms presented on the spatial light modulator  
25 30, to wavefront transformation into a virtual image or a real image.

[0061] The illumination light source section 10 has three point light sources for emitting their respective illumination light components of mutually different wavelengths (red, green, and blue). These three point light sources are located at mutually different positions on a straight line parallel to the x-axis. The point light source for emitting the blue illumination light component of the shortest wavelength is located at a position  $B(0,0)$  on the optical axis of the illumination optical system. The point light source for emitting the red illumination light component is located at a position  $R(x_r,0)$ . The point light source for emitting the green illumination light component is located at a position  $G(x_g,0)$ . Each point light source includes, for example, a light emitting diode, a laser diode, or the like and emits an illumination light component with excellent monochromaticity. The point light sources each are sequentially lit as pulsed in time series.

[0062] The lens 20 has the optical axis parallel to the z-axis, and collimates each of illumination light components of the respective wavelengths emitted from the three corresponding point light sources of the illumination light source section 20, into a parallel plane wave and makes the parallel plane waves incident from mutually different incident directions to the



spatial light modulator 30. In a case where the lens 20 is comprised of a single convex lens, the spacing between each of the three point light sources and the lens 20 is equal to the focal length of the lens 20.

5 Since the three point light sources are located at the aforementioned positions, the blue illumination light component is normally incident to the spatial light modulator 30, while the illumination light components of red and green are obliquely incident to the spatial  
10 light modulator 30. The lens 20 is preferably an achromatic lens having an identical focal length for the wavelengths of the respective illumination light components.

[0063] The spatial light modulator 30 is a  
15 transmission type spatial light modulator having the discrete pixel structure, and sequentially presents holograms associated with the three respective wavelengths, in time series. These holograms may be amplitude holograms or phase holograms. Then the  
20 spatial light modulator 30 sequentially presents holograms associated with wavelengths at respective points of time, in synchronism with time-series sequential incidence of the illumination light components of the respective wavelengths from the lens  
25 20. This results in sequentially outputting reproduced light components of the respective wavelengths in time

series. Namely, the field sequential system is adopted for the spatial light modulator 30.

[0064] The lens 40 functions to subject each of reproduced images of the three wavelengths generated from the holograms presented on the spatial light modulator 30, to wavefront transformation into a virtual image or a real image, and then to make each image pass on the plane of the mask 50. In a case where the lens 40 is comprised of a single convex lens, the spacing between the lens 40 and the mask 50 is equal to the focal length of the lens 40. The lens 40 is preferably an achromatic lens having an identical focal length for the wavelengths of the respective illumination light components.

[0065] The mask 50 is provided on the focal plane of the lens 40 and has an aperture 51. This aperture 51 has a rectangular shape each side of which is parallel to the x-axis or to the y-axis, and has a function of selecting only diffracted waves of zero order generated from the spatial light modulator 30, a function of blocking zero-order directly transmitted light from the spatial light modulator 30, and a function of blocking unwanted light of light components of zero-order diffracted waves which are generated from the holograms presented on the spatial light modulator 30 and which form a real image or a conjugate image to

cause the problem of double images. The zero-order directly transmitted light from the spatial light modulator 30 is light contributing to image formation of the light sources as condensed by the lens 40, and becomes background light of a reproduced image to degrade contrast. The aperture 51 is located in an area in which diffracted waves of any order out of the reproduced light components of the three wavelengths are superimposed on each other after the wavefront transformation by the lens 40. Particularly, in the present embodiment, the aperture 51 is located in an area where the zero-order diffracted waves of the respective reproduced light components of the three wavelengths are superimposed on each other after the wavefront transformation by the lens 40. In this manner, the incident directions of the respective illumination light components of the three wavelengths to the spatial light modulator 30 are set by the illumination optical system.

[0066] Fig. 2 is an illustration for explaining the illumination optical system and spatial light modulator 30 of the 3D image display apparatus 1 according to the first embodiment. As shown in this figure, the blue point light source in the illumination light source section 10 is located on the optical axis of the lens 20, and the illumination light component

emitted from this blue point light source is collimated by the lens 20 into a parallel plane wave  $60_b$  to be normally incident to the spatial light modulator 30. The red point light source is located at the position separated from the optical axis of the lens 20, and the illumination light component emitted from this red point light source is collimated by the lens 20 into a parallel plane wave  $60_r$  traveling in a direction  $61_r$  inclined relative to the z-axis to be obliquely incident to the spatial light modulator 30. The green point light source is located in a manner similar to the red point light source.

[0067] Fig. 3 is an illustration for explaining the illumination optical system of the 3D image display apparatus 1 according to the first embodiment. As shown in this figure, the illumination light source section 10 includes three monochromatic light sources  $11_r$ ,  $11_g$ , and  $11_b$  of mutually different output wavelengths, and three pinholes  $12_r$ ,  $12_g$ , and  $12_b$ . The pinhole  $12_r$  is located at the position  $R(x_r, 0)$  in proximity to the monochromatic light source  $11_r$  for emitting the red light, and outputs the light emitted from this monochromatic light source  $11_r$  toward the lens 20. The pinhole  $12_g$  is located at the position  $G(x_g, 0)$  in proximity to the monochromatic light source  $11_g$  for emitting the green light, and outputs the light

emitted from this monochromatic light source 11<sub>g</sub>,  
toward the lens 20. The pinhole 12<sub>b</sub> is located at the  
position B(0,0) in proximity to the monochromatic light  
source 11<sub>b</sub> for emitting the blue light, and outputs the  
5 light emitted from this monochromatic light source 11<sub>b</sub>,  
toward the lens 20. By adopting this configuration,  
even in a case where each of the monochromatic light  
sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> cannot be treated as a point  
light source, the illumination light component emitted  
10 from each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> can be  
treated as light emitted from a point light source and  
the lens 20 can convert it into an ideal parallel plane  
wave.

[0068] Next, the operation of the 3D image display  
15 apparatus 1 according to the first embodiment will be  
described. In a case where an element capable of  
modulating both the amplitude and phase for each pixel  
is applied as the spatial light modulator 30, neither  
transmitted light nor a conjugate image is generated.  
20 However, in a case where an element capable of  
modulating only one of the amplitude and phase for each  
pixel is applied as the spatial light modulator 30,  
transmitted light and a conjugate image are generated.  
The below will describe the latter case.

25 [0069] Fig. 4 is an illustration for explaining a  
display operation of a luminescent point in a 3D image

where the blue illumination light component is normally incident to the spatial light modulator 30 in the 3D image display apparatus 1 according to the first embodiment. Fig. 5 is an illustration for explaining a hologram presented on the spatial light modulator 30 when the blue illumination light component is normally incident to the spatial light modulator 30 in the 3D image display apparatus 1 according to the first embodiment. When a hologram  $31_b$  associated with the blue illumination light component is presented on the spatial light modulator 30, the blue illumination light component of a parallel plane wave  $60_b$  is normally incident to the spatial light modulator 30. The hologram  $31_b$  associated with the blue illumination light component is presented on a half plane (an area of  $y < 0$ ) on the spatial light modulator 30. When the illumination light component is incident to the spatial light modulator 30, a reproduced image  $62_b$  and a conjugate image  $63_b$  of a luminescent point in the 3D image are formed on the optical axis, and zero-order transmitted light appears. The reproduced image  $62_b$  of the luminescent point is subjected to wavefront transformation into an area  $52_b$  (in the area of  $y < 0$ ) on the mask 50 by the lens 40. On the other hand, the conjugate image  $63_b$  of the luminescent point is subjected to wavefront transformation into an area  $53_b$

(in the area of  $y > 0$ ) on the mask 50 by the lens 40. The zero-order transmitted light is converged at the position (0,0) on the mask 50 by the lens 40. Then the conjugate image and the zero-order transmitted light are blocked by the mask 50, and the reproduced image only can be observed through the aperture 51.

[0070] Fig. 6 is an illustration for explaining a display operation of a luminescent point in a 3D image in a case where an illumination light component is obliquely incident to the spatial light modulator 30 in the 3D image display apparatus 1 according to the first embodiment. A hologram presented at this time on the spatial light modulator 30 is assumed to be similar to the hologram shown in Fig. 5. In this case, the illumination light component of a parallel plane wave 60 is obliquely incident to the spatial light modulator 30, whereupon a reproduced image 62 and a conjugate image 63 of the luminescent point in the 3D image are formed on the optical axis 61 of the parallel plane wave 60. This is different from the locations of the reproduced image and conjugate image shown in Fig. 4.

[0071] In order to avoid the disagreement between the reproduced image upon the normal incidence and the reproduced image upon the oblique incidence, the present embodiment is arranged to prepare the holograms presented upon the oblique incidence on the spatial

light modulator 30, by either of two methods described below.

[0072] The first hologram preparing method is a method of calculating the holograms upon the oblique incidence. An object light component from a luminescent point forming a 3D image is expressed by a spherical wave. An object light component  $O_{ij}$  generated from a luminescent point at a position  $(x_0, y_0, L_0)$  is expressed by Eqs (1a), (1b) below, at a position  $(x_i, y_j, 0)$  on the spatial light modulator 30.

$$O_{i,j} = \frac{1}{r} \exp(jkr) \quad \dots (1a)$$

$$r = \sqrt{(x_i - x_0)^2 + (y_j - y_0)^2 + L_0^2} \quad \dots (1b)$$

[0073] Here  $r$  represents a distance from the luminescent point at the position  $(x_0, y_0, L_0)$  to the position  $(x_i, y_j, 0)$  on the spatial light modulator 30, and  $k$  the wave number of the object light component. A reference light component  $R_{ij}$  being a parallel plane wave with an incidence angle  $\theta$  is expressed by Eq (2) below, at the position  $(x_i, y_j, 0)$  on the spatial light modulator 30.

$$R_{i,j} = \exp(jk(L_0 - (x_i - x_0) \sin \theta)) \quad \dots (2)$$

[0074] When the synthesis of the object light component and the reference light component on the hologram plane is expressed by Eq (3) below, the phase



$\phi_{i,j}$  of light is expressed by Eq (4) below and the light intensity by Eq (5) below, at the position  $(x_i, y_j, 0)$  on the hologram plane.

$$O_{i,j} + R_{i,j} = A + jB \quad \cdots (3)$$

$$\phi_{i,j} = \tan^{-1}(B / A) \quad \cdots (4)$$

$$|O_{i,j} + R_{i,j}|^2 = |O_{i,j}|^2 + |R_{i,j}|^2 + O_{i,j} R_{i,j}^* + O_{i,j}^* R_{i,j} \quad \cdots (5)$$

[0075] Since the illumination light component incident to the spatial light modulator 30 upon reproduction is equivalent to the reference light component R, a computer-generated hologram is prepared from the third term in the right-hand side of above Eq (5).

[0076] Concerning the calculation range of the computer-generated hologram, the maximum spatial frequency of the hologram is restricted by the pixel pitch of the spatial light modulator 30, because the spatial light modulator 30 displaying the hologram has the discrete pixel structure. For this reason, the calculation range is a range in which phase differences between synthetic wavefronts of the object light component and the reference light component at two adjacent pixels are not more than  $\pi$ , i.e., a half plane determined by a region satisfying the conditions

expressed by Expressions (6a), (6b) below.

$$|\phi_{i,j} - \phi_{i-1,j}| \leq \pi \quad \dots (6a)$$

$$|\phi_{i,j} - \phi_{i,j-1}| \leq \pi \quad \dots (6b)$$

[0077] Figs. 7 and 8 are illustrations each for explaining a hologram prepared by the first hologram preparing method. Fig. 7 shows a presentation range of hologram 31 on the spatial light modulator 30 in a case where a point light source is located at the position (0,y). Fig. 8 shows a presentation range of hologram 31 on the spatial light modulator 30 in a case where a point light source is located at the position (x,0). As shown in these figures, the hologram 31 presented on the spatial light modulator 30 is similar to one obtained by translating the hologram 31<sub>b</sub> shown in Fig. 5, in parallel with the x-axis or with the y-axis.

[0078] Fig. 9 is an illustration for explaining a display operation of a luminescent point in a 3D image where an illumination light component is obliquely incident to the spatial light modulator 30 during presentation of the hologram 31 shown in Fig. 7, on the spatial light modulator 30. As shown in this figure, when the illumination light component of a parallel plane wave 60 is obliquely incident to the spatial light modulator 30, a reproduced image 62 of the luminescent point in the 3D image is formed on the

optical axis 61. This coincides with the location of the reproduced image shown in Fig. 4.

[0079] The second hologram preparing method is a method of translating a hologram presentation range.

5 The foregoing first hologram preparing method requires the process of calculating the product of the object light component and the reference light component in calculation of the hologram because of the oblique incidence of the reference light component, so that the  
10 computation time is longer than in the case of the normal incidence of the reference light component. In contrast to it, the second hologram preparing method described below is able to calculate the hologram within a short time by making use of the similarity of  
15 the hologram upon the oblique incidence to that upon the normal incidence as described above.

[0080] Fig. 10 is an illustration for explaining the second hologram preparing method. Supposing the hologram presented on the spatial light modulator 30 is  
20 the same as the hologram shown in Fig. 5, a location of luminescent point 62' generated therefrom is a distance D apart in the x-axis direction from a location of desired luminescent point 62. Therefore, the hologram to be presented can be obtained by translating the  
25 presentation location of the hologram by this distance D. This translation distance D is expressed by Eq (7)

below.

$$D = L \cdot \tan \theta \quad \dots (7)$$

[0081] Here L represents the distance between the luminescent point and the hologram plane. Furthermore,  $\theta$  is an incidence angle of the parallel plane wave to the hologram plane, and this incidence angle  $\theta$  is expressed by Eq (8) below.

$$\theta = (\text{distance between light source and optical axis}) / (\text{front focal length of lens 20}) \quad (8)$$

[0082] The first or second hologram preparing method described above enables the reproduced images to be acquired without deviation between upon the oblique incidence and upon the normal incidence.

[0083] Next, reproduced light components generated from the spatial light modulator 30 upon incidence of the illumination light components of the respective wavelengths will be described.

[0084] Figs. 11 to 15 are illustrations for explaining an ideal case presented as a comparative example. It is assumed that the spatial light modulator 30 herein is an element capable of modulating only one of the amplitude and phase for each pixel and that a hologram is presented on the half plane ( $y < 0$ ) of the spatial light modulator 30 as shown in Fig. 5, and the case described herein is assumed to be an ideal case where all the point light sources of the three

wavelengths are located at the position (0,0) as shown in Fig. 11.

[0085] In this case, as shown in Fig. 12, the zero-order diffracted wave of the red reproduced light component of the longest wavelength generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area 52<sub>r</sub> defined by four points R1 to R4 expressed by Expressions (9) below, on the rear focal plane of the lens 40.

$$\begin{aligned} R1(-\lambda_r f / 2P_x, 0) \\ R2(-\lambda_r f / 2P_x, -\lambda_r f / 2P_y) \\ R3(+\lambda_r f / 2P_x, -\lambda_r f / 2P_y) \\ R4(+\lambda_r f / 2P_x, 0) \end{aligned} \quad \dots (9)$$

[0086] Here  $\lambda_r$  is the wavelength of the red reproduced light component,  $f$  the focal length of the lens 40,  $P_x$  the pixel pitch in the x-axis direction of the spatial light modulator 30, and  $P_y$  the pixel pitch in the y-axis direction of the spatial light modulator 30. A red conjugate image is subjected to wavefront transformation into a rectangular region defined by four points R1 and R4-R6 expressed by Expressions (10) below, on the rear focal plane of the lens 40.

$$\begin{aligned} R1(-\lambda_r f / 2P_x, 0) \\ R4(+\lambda_r f / 2P_x, 0) \\ R5(+\lambda_r f / 2P_x, +\lambda_r f / 2P_y) \\ R6(-\lambda_r f / 2P_x, +\lambda_r f / 2P_y) \end{aligned} \quad \dots (10)$$

[0087] With the rectangular region defined by four points R2, R3, R5, and R6, as a unit, zero-order and higher-order reproduced images and conjugate images are two-dimensionally periodically formed on the rear focal plane of the lens 40.

[0088] Likewise, as shown in Fig. 13, the zero-order diffracted wave of the green reproduced light component of the wavelength  $\lambda_g$  generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area 52<sub>g</sub> defined by four points G1-G4 expressed by Expressions (11) below, on the rear focal plane of lens 40.

$$\begin{aligned} G1(-\lambda_g f / 2P_x, 0) \\ G2(-\lambda_g f / 2P_x, -\lambda_g f / 2P_y) \\ G3(+\lambda_g f / 2P_x, -\lambda_g f / 2P_y) \\ G4(+\lambda_g f / 2P_x, 0) \end{aligned} \quad \dots (11)$$

[0089] In addition, as shown in Fig. 14, the zero-order diffracted wave of the blue reproduced light component of the shortest wavelength  $\lambda_b$  generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area 52<sub>b</sub> defined by four points B1-B4 expressed by Expressions (12) below, on the rear focal plane of the lens 40.

$$\begin{aligned}
& B1(-\lambda_b f / 2P_x, 0) \\
& B2(-\lambda_b f / 2P_x, -\lambda_b f / 2P_y) \quad \dots (12) \\
& B3(+\lambda_b f / 2P_x, -\lambda_b f / 2P_y) \\
& B4(+\lambda_b f / 2P_x, 0)
\end{aligned}$$

[0090] When the wavefront transformation areas 52<sub>r</sub>, 52<sub>g</sub>, and 52<sub>b</sub> on the rear focal plane of the lens 40 are shown in a superimposed state as shown in Fig. 15, the green wavefront transformation area 52<sub>g</sub> is included in the red wavefront transformation area 52<sub>r</sub>, and the blue wavefront transformation area 52<sub>b</sub> is included in the green wavefront transformation area 52<sub>g</sub>. Therefore, a full-color 3D image can be observed when the aperture 51 of the mask 50 is set to be equivalent to the blue wavefront transformation area 52<sub>b</sub> and when the reproduced light components of the respective colors having passed through this aperture 52 are observed.

[0091] However, the ideal case where the three point light sources are located at the common position as shown in Fig. 11 is practically impossible. In the present embodiment, therefore, the three point light sources are located at mutually different positions, an illumination light component of one wavelength out of them is made normally incident to the spatial light modulator 30, and the other illumination light components of remaining two wavelengths are made

obliquely incident to the spatial light modulator 30.

[0092] Figs. 16 to 19 are illustrations to illustrate the 3D image display apparatus 1 and 3D image display method according to the first embodiment.

5 Fig. 16 is an illustration showing arrangement of the three point light sources in the illumination light source section 10 of the 3D image display apparatus 1 according to the first embodiment. Fig. 17 is an

illustration showing a wavefront transformation area of the zero-order diffracted wave of the red reproduced light component at the location of mask 50 in the 3D image display apparatus 1 according to the first embodiment. Fig. 18 is an illustration showing a

10 wavefront transformation area of the zero-order diffracted wave of the green reproduced light component at the location of mask 50 in the 3D image display apparatus 1 according to the first embodiment. The

15 wavefront transformation area of the zero-order diffracted wave of the blue reproduced light component at the location of mask 50 in the 3D image display apparatus 1 according to the first embodiments is the

20 same as that in the case shown in Fig. 14. Fig. 19 is an illustration showing the wavefront transformation areas of the zero-order diffracted waves of the respective reproduced light components of red, green, and blue at the location of mask 50 in the 3D image



display apparatus 1 according to the first embodiment.

[0093] In the first embodiment, as shown in Fig. 16, the red point light source is located at the position  $R(x_r, 0)$ , the green point light source at the position  $G(x_g, 0)$ , and the blue point light source at the position  $B(0, 0)$ . Here  $x_r$  and  $x_g$  each are expressed by Expressions (13) below.

$$\begin{aligned} x_r &= +\{(\lambda_g f / 2P) - (\lambda_b f / 2P)\} / M \\ x_g &= -\{(\lambda_g f / 2P) - (\lambda_b f / 2P)\} / M \quad \dots (13) \\ M &= -f_2 / f_1 \end{aligned}$$

[0094] Here  $f_1$  represents the focal length of lens 20, and  $f_2$  the focal length of the lens 40.  $M$  is a magnification of the optical system.

[0095] In this case, as shown in Fig. 17, the zero-order diffracted wave of the red reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area  $52_r$  based on a position  $R'(\lambda_g f / 2P - \lambda_b f / 2P, 0)$ , on the rear focal plane of lens 40. As shown in Fig. 18, the zero-order diffracted wave of the green reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area  $52_g$  based on a position  $G'(-\lambda_g f / 2P + \lambda_b f / 2P, 0)$ , on the rear focal plane of lens 40. As shown in Fig. 14, the zero-order diffracted

wave of the blue reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area  $52_b$  based on the position  $B'(0,0)$ , on the rear focal plane of lens 40.

[0096] When the wavefront transformation areas  $52_r$ ,  $52_g$ , and  $52_b$  on the rear focal plane of lens 40 are shown in a superimposed state as shown in Fig. 19, the green wavefront transformation area  $52_g$  is included in the red wavefront transformation area  $52_r$ , and the blue wavefront transformation area  $52_b$  is included in the green wavefront transformation area  $52_g$ . Therefore, a full-color 3D image can be observed when the aperture 51 of the mask 50 is made coincident with the blue wavefront transformation area  $52_b$  and when the reproduced light components of the respective colors having passed through the aperture 52 are observed.

[0097] Next, a specific example of the first embodiment will be described. The spatial light modulator 30 used herein was a data projection liquid crystal panel LCX023AL (pixel pitch  $P = 26 \mu\text{m}$ ) available from Sony Corp. The lens 20 was an achromatic lens having the focal length of 600 mm, and the lens 40 an achromatic lens having the focal length of 150 mm. The monochromatic light source 11<sub>r</sub> for emitting red light was a light emitting diode CL-280SR-

C (wavelength 650 nm; dimensions 1.0 (L) × 0.5 (W) × 0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source 11<sub>g</sub> for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source 11<sub>b</sub> for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0098] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (-0.69 mm, 0) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (+0.69 mm, 0).

The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150 μm. The incidence angle of the red illumination light component to the spatial light modulator 30 was set at +0.07°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at -0.07°. The size of the aperture 51 of the mask 50 was 2.7 mm (W) × 1.3 mm (H). The drive frequency of the spatial light modulator 30 was 70 Hz, the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially

activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

[0099] Next, modification example A of the 3D image display apparatus and 3D image display method according to the first embodiment will be described.

The description heretofore concerned the arrangement of the three point light sources along the x-axis direction, whereas this modification example A concerns

arrangement of the three point light sources along the y-axis direction. Figs. 20 to 23 are illustrations for explaining modification example A of the 3D image display apparatus 1 and 3D image display method according to the first embodiment. Fig. 20 is an

illustration showing arrangement of the three point light sources in the illumination light source section 10 in modification example A of the 3D image display apparatus 1 according to the first embodiment. Fig. 21

is an illustration showing the wavefront transformation area of the zero-order diffracted wave of the red reproduced light component at the location of mask 50, in modification example A of the 3D image display apparatus 1 according to the first embodiment. Fig. 22

is an illustration showing the wavefront transformation area of the zero-order diffracted wave of the green reproduced light component at the location of mask 50,

in modification example A of the 3D image display apparatus 1 according to the first embodiment. In modification example A of the 3D image display apparatus 1 according to the first embodiment, the wavefront transformation area of the zero-order diffracted wave of the blue reproduced light component at the location of mask 50 is the same as that in the case shown in Fig. 14. Fig. 23 is an illustration showing the wavefront transformation areas of the zero-order diffracted waves of the respective reproduced light components of red, green, and blue at the location of mask 50, in modification example A of the 3D image display apparatus 1 according to the first embodiment.

[0100] In this modification example A, as shown in Fig. 20, the red point light source is located at the position  $R(0, y_r)$ , the green point light source at the position  $G(0, y_g)$ , and the blue point light source at the position  $B(0, 0)$ . Here  $y_r$  and  $y_g$  each are expressed by Eqs (14) below.

$$\begin{aligned} y_r &= \{(\lambda_r f / 2P) - (\lambda_b f / 2P)\} / M \\ y_g &= \{(\lambda_g f / 2P) - (\lambda_b f / 2P)\} / M \end{aligned} \quad \dots (14)$$

[0101] In this case, as shown in Fig. 21, the zero-order diffracted wave of the red reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40

into a rectangular area  $52_r$  based on a position  $R'(0, \lambda_r f/2P - \lambda_b f/2P, 0)$ , on the rear focal plane of lens 40. In addition, as shown in Fig. 22, the zero-order diffracted wave of the green reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a rectangular area  $52_g$  based on a position  $G'(0, \lambda_g f/2P - \lambda_b f/2P, 0)$ , on the rear focal plane of lens 40. Furthermore, as shown in Fig. 14, the zero-order diffracted wave of the blue reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into the rectangular area  $52_b$  based on the position  $B'(0, 0)$ , on the rear focal plane of lens 40.

[0102] When the wavefront transformation areas  $52_r$ ,  $52_g$ , and  $52_b$  on the rear focal plane of lens 40 are shown in a superimposed state as shown in Fig. 23, the green wavefront transformation area  $52_g$  is included in the red wavefront transformation area  $52_r$ , and the blue wavefront transformation area  $52_b$  is included in the green wavefront transformation area  $52_g$ . Therefore, a full-color 3D image can be observed when the aperture 51 of the mask 50 is made coincident with the blue wavefront transformation area  $52_b$  and when the reproduced light components of the respective colors having passed through this aperture 52 are observed.

[0103] Next, a specific example of modification example A of the first embodiment will be described. The spatial light modulator 30 used herein was a data projection liquid crystal panel LCX023AL (pixel pitch  $P = 26 \mu\text{m}$ ) available from Sony Corp. The lens 20 was an achromatic lens having the focal length of 600 mm, and the lens 40 an achromatic lens having the focal length of 150 mm. The monochromatic light source  $11_r$  for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions 1.0 (L)  $\times$  0.5 (W)  $\times$  0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source  $11_g$  for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L)  $\times$  0.6 (W)  $\times$  1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source  $11_b$  for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L)  $\times$  0.6 (W)  $\times$  1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0104] The monochromatic light source  $11_r$  for emitting red light was placed at the position (0, -2.08 mm) and the monochromatic light source  $11_g$  for emitting green light at the position (0, -0.69 mm). The aperture diameter of each of the pinholes  $12_r$ ,  $12_g$ , and  $12_b$  was 150  $\mu\text{m}$ . The incidence angle of the red illumination light component to the spatial light

modulator 30 was set at  $-0.20^\circ$ , and the incidence angle of the green illumination light component to the spatial light modulator 30 at  $-0.07^\circ$ . The size of the aperture 51 of the mask 50 was 2.7 mm (W)  $\times$  1.3 mm (H).

5 The drive frequency of the spatial light modulator 30 was 70 Hz, the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources  $11_r$ ,  $11_g$ , and  $11_b$  were sequentially  
10 activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

[0105] Next, modification example B of the 3D image display apparatus and 3D image display method  
15 according to the first embodiment will be described. In the foregoing modification example A the three point light sources were arranged in the y-axis direction on the half plane ( $y < 0$ ), whereas in this modification example B the red point light source is placed on one  
20 half plane ( $y < 0$ ) and the green point light source on the other half plane ( $y > 0$ ). Figs. 24 to 26 are illustrations for explaining modification example B of the 3D image display apparatus 1 and 3D image display method according to the first embodiment. Fig. 24 is  
25 an illustration showing arrangement of the three point light sources in the illumination light source section



10, in modification example B of the 3D image display apparatus 1 according to the first embodiment. Fig. 25 is an illustration showing the wavefront transformation area of the zero-order diffracted wave of the green reproduced light component at the location of mask 50, in modification example B of the 3D image display apparatus 1 according to the first embodiment. In modification example B of the 3D image display apparatus 1 according to the first embodiment, the wavefront transformation area of the zero-order diffracted wave of the red reproduced light component at the location of mask 50 is the same as that in the case shown in Fig. 21. In modification example B of the 3D image display apparatus 1 according to the first embodiment, the wavefront transformation area of the zero-order diffracted wave of the blue reproduced light component at the location of mask 50 is the same as that in the case shown in Fig. 14. Fig. 26 is an illustration showing the wavefront transformation areas of the zero-order diffracted waves of the respective reproduced light components of red, green, and blue at the location of mask 50, in modification example B of the 3D image display apparatus 1 according to the first embodiment.

[0106] In this modification example B, as shown in Fig. 24, the red point light source is located at the

position  $R(0, y_r)$ , the green point light source at the position  $G(0, y_g)$ , and the blue point light source at the position  $B(0, 0)$ . Here  $y_r$  and  $y_g$  each are expressed by Eqs (15) below.

$$\begin{aligned} y_r &= \{(\lambda_r f / 2P) - (\lambda_b f / 2P)\} / M \\ y_g &= -(\lambda_b f / 2P) / M \end{aligned} \quad \dots (15)$$

[0107] In this case, as shown in Fig. 21, the zero-order diffracted wave of the red reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into a lower rectangular area  $52_r$  based on the position  $R'(0, \lambda_r f / 2P - \lambda_b f / 2P, 0)$ , on the rear focal plane of lens 40. In addition, as shown in Fig. 25, the zero-order diffracted wave of the green reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into an upper rectangular area  $52_g$  based on the position  $G'(0, -\lambda_b f / 2P, 0)$ , on the rear focal plane of lens 40. Furthermore, as shown in Fig. 14, the zero-order diffracted wave of the blue reproduced light component generated from the spatial light modulator 30 is subjected to wavefront transformation by the lens 40 into the lower rectangular area  $52_b$  based on the position  $B'(0, 0)$ , on the rear focal plane of lens 40.

[0108] When the wavefront transformation areas  $52_r$ ,  $52_g$ , and  $52_b$  on the rear focal plane of lens 40 are

shown in a superimposed state as shown in Fig. 26, the green wavefront transformation area  $52_g$  is included in the red wavefront transformation area  $52_r$ , and the blue wavefront transformation area  $52_b$  is included in the green wavefront transformation area  $52_g$ . Therefore, a full-color 3D image can be observed when the aperture 51 of the mask 50 is made coincident with the blue wavefront transformation area  $52_b$  and when the reproduced light components of the respective colors having passed through this aperture 52 are observed.

[0109] Next, a specific example of modification example B of the first embodiment will be described. The spatial light modulator 30 used herein was a data projection liquid crystal panel LCX023AL (pixel pitch  $P = 26 \mu\text{m}$ ) available from Sony Corp. The lens 20 was an achromatic lens having the focal length of 200 mm, and the lens 40 an achromatic lens having the focal length of 150 mm. The monochromatic light source  $11_r$  for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions 1.0 (L)  $\times$  0.5 (W)  $\times$  0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source  $11_g$  for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L)  $\times$  0.6 (W)  $\times$  1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source  $11_b$  for emitting blue light

was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0110] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (0, -0.69 mm) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (0, +1.36 mm). The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150 μm. The incidence angle of the red illumination light component to the spatial light modulator 30 was set at -0.20°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at +0.39°. The size of the aperture 51 of the mask 50 was 2.7 mm (W) × 1.3 mm (H). The drive frequency of the spatial light modulator 30 was 70 Hz, the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

[0111] As described above, the 3D image display apparatus 1 and 3D image display method according to the first embodiment, including modification example A and modification example B, are able to provide color

display of a clear 3D image even with use of the spatial light modulator 30 of a low resolution, because the incident directions of the respective illumination light components of the three wavelengths to the spatial light modulator 30 are properly set and the zero-order diffracted waves of the respective reproduced light components of the three wavelengths generated from the spatial light modulator 30 are superimposed on each other in the aperture 51 after the wavefront transformation by the lens 40. There is no need for the half mirror for superposition of the reproduced light components of the three wavelengths as required in conventional technology 2, and no need for the high-speed shutter as required in the third conventional technology, and thus the present embodiment successfully provides the compact and inexpensive 3D image display apparatus.

(Second Embodiment)

[0112] Next, the second embodiment of the 3D image display apparatus and 3D image display method according to the present invention will be described. Fig. 27 is an illustration showing a configuration of the 3D image display apparatus 2 according to the second embodiment. The 3D image display apparatus 2 shown in this figure has an illumination light source section 10, a lens 20, a half mirror 25, a reflection type spatial light

modulator 30, a lens 40, and a mask 50. The illumination light source section 10, lens 20, and half mirror 25 constitute an illumination optical system for converting each of illumination light components of three wavelengths into a parallel plane wave and making the parallel plane waves incident from mutually different incident directions to the spatial light modulator 30. The half mirror 25 and lens 40 constitute a reproduced image transforming optical system for subjecting each of reproduced light components of the three wavelengths generated from holograms presented on the spatial light modulator 30, to wavefront transformation. The illumination optical system and the reproduced image transforming optical system share the half mirror 25.

[0113] When compared with the first embodiment, the 3D image display apparatus 2 and 3D image display method according to the second embodiment are similar thereto in each of the illumination light source section 10, lens 20, lens 40, and mask 50, but are different therefrom in mutual arrangement of the components due to the spatial light modulator 30 being the reflection type spatial light modulator. When compared with the first embodiment, the operation of the 3D image display apparatus 2, and the 3D image display method according to the second embodiment are

different therefrom in that each illumination light component, after converted into a parallel plane wave by the lens 20, passes through the half mirror 25 to enter the spatial light modulator 30, in that the reproduced light components emerge on the same side as the side where the illumination light components are incident to the spatial light modulator 30, and in that each reproduced light component is subjected to wavefront transformation by the lens 40 after reflected by the half mirror 25. For the rest, the operation of the 3D image display apparatus 2, and the 3D image display method according to the second embodiment are theoretically similar to those in the first embodiment (including modification examples A and B).

[0114] Next, a specific example of the second embodiment will be described. The spatial light modulator 30 used herein was a reflection type liquid crystal panel MD800G6 for micro monitor (pixel pitch  $P = 12.55 \mu\text{m}$ ) available from Micro Display Corp. The lens 20 was an achromatic lens having the focal length of 300 mm, and the lens 40 an achromatic lens having the focal length of 60 mm. The monochromatic light source 11<sub>r</sub> for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions 1.0 (L)  $\times$  0.5 (W)  $\times$  0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source 11<sub>g</sub> for

emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source 11<sub>b</sub> for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0115] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (-0.72 mm, 0) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (+0.72 mm, 0). The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150 μm. The incidence angle of the red illumination light component to the spatial light modulator 30 was set at -0.14°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at +0.14°. The size of the aperture 51 of the mask 50 was 2.2 mm (W) × 1.1 mm (H). The drive frequency of the spatial light modulator 30 was 90 Hz, the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.



(Third Embodiment)

[0116] Next, the third embodiment of the 3D image display apparatus and 3D image display method according to the present invention will be described. Fig. 28 is an illustration showing a configuration of the 3D image display apparatus 3 according to the third embodiment. The 3D image display apparatus 3 shown in this figure has an illumination light source section 10, a half mirror 25, a lens 20, a reflection type spatial light modulator 30, and a mask 50. The illumination light source section 10, half mirror 25, and lens 20 constitute an illumination optical system for converting each of illumination light components of three wavelengths into a parallel plane wave and making the parallel plane waves incident from mutually different incident directions to the spatial light modulator 30. The lens 20 and half mirror 25 constitute a reproduced image transforming optical system for subjecting each of reproduced light components of the three wavelengths generated from holograms presented on the spatial light modulator 30, to wavefront transformation. The illumination optical system and the reproduced image transforming optical system share the lens 20 and the half mirror 25.

[0117] When compared with the second embodiment, the 3D image display apparatus 3 and 3D image display

method according to the third embodiment are similar thereto in each of the illumination light source section 10, spatial light modulator 30, and mask 50, but are different therefrom in mutual arrangement of the components because of the spatial light modulator 30 being the reflection type spatial light modulator. When compared with the case of the second embodiment, the operation of the 3D image display apparatus 3, and the 3D image display method according to the third embodiment are different therefrom in that the lens 20 also acts as the lens 40, in that each illumination light component, after passing through the half mirror 25, is converted into a parallel plane wave by the lens 20 to enter the spatial light modulator 30, in that the reproduced light components emerge on the same side as the side where the illumination light components are incident to the spatial light modulator 30, and in that each reproduced light component is subjected to wavefront transformation as reflected by the half mirror 25 after passing through the lens 20. For the rest, the operation of the 3D image display apparatus 2, and the 3D image display method according to the third embodiment are theoretically almost similar to those in the second embodiment.

[0118] Since in the third embodiment the lens 20 also acts as the lens 40, the focal lengths of the

illumination optical system and the reproduced image transforming optical system are equal to each other. Therefore, where the three point light sources are located at positions  $R(x_r, 0)$ ,  $G(x_g, 0)$ , and  $B(0, 0)$ , reference points of the wavefront transformation areas of the respective colors on the plane of mask 50 are positions  $R(-x_r, 0)$ ,  $G(-x_g, 0)$ , and  $B(0, 0)$ . The area where all the wavefront transformation areas  $52_r$ ,  $52_g$ , and  $52_b$  of the respective colors on the plane of mask 50 are superimposed on each other (i.e., the area of the aperture 51 of the mask 50) can be narrower than in the case of the first embodiment or the second embodiment, as shown in Fig. 29.

[0119] Next, a specific example of the third embodiment will be described. The spatial light modulator 30 used herein was a reflection type liquid crystal panel MD800G6 for micro monitor (pixel pitch  $P = 12.55 \mu\text{m}$ ) available from Micro Display Corp. The lens 20 also acting as the lens 40 was an achromatic lens having the focal length of 60 mm. The monochromatic light source  $11_r$  for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions  $1.0 \text{ (L)} \times 0.5 \text{ (W)} \times 0.6 \text{ (H)}$ ) available from Citizen Electronics Co., Ltd. The monochromatic light source  $11_g$  for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm;

dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source 11<sub>b</sub> for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0120] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (-0.65 mm, 0) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (+0.65 mm, 0). The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150 μm. The incidence angle of the red illumination light component to the spatial light modulator 30 was set at -0.62°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at +0.62°. The size of the aperture 51 of the mask 50 was 1.5 mm (W) × 1.1 mm (H). The drive frequency of the spatial light modulator 30 was 90 Hz, the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

(Fourth Embodiment)

[0121]       Next, the fourth embodiment of the 3D image display apparatus and 3D image display method according to the present invention will be described. Fig. 30 is an illustration showing a configuration of the 3D image display apparatus 4 according to the fourth embodiment. The 3D image display apparatus 4 shown in this figure has an illumination light source section 10, a lens 20, a spatial light modulator 30 of the transmission type, a lens 40, and a mask 50. The illumination light source section 10 and the lens 20 constitute an illumination optical system for converting each of illumination light components of three wavelengths into a parallel plane wave and making the parallel plane waves incident from mutually different incident directions to the spatial light modulator 30. The lens 40 constitutes a reproduced image transforming optical system for subjecting each of reproduced images of the three wavelengths generated from holograms presented on the spatial light modulator 30, to wavefront transformation into a virtual image or a real image.

[0122]       The illumination light source section 10 has three point light sources for emitting their respective illumination light components of mutually different wavelengths (red, green, and blue). These three point light sources are located at mutually different positions on a straight line parallel to the

x-axis. The point light source for emitting the blue illumination light component of the shortest wavelength is located at the position  $B(0,0)$  on the optical axis of the illumination optical system. The point light source for emitting the red illumination light component is located at the position  $R(x_r,0)$  or  $R(0,y_r)$ . The point light source for emitting the green illumination light component is located at the position  $G(x_g,0)$ . Each point light source includes, for example, a light emitting diode, a laser diode, or the like and emits an illumination light component with excellent monochromaticity. The point light sources each are sequentially lit as pulsed in time series. The configuration of this illumination light source section 10 is preferably the same as that in Fig. 3.

[0123] The lens 20 has the optical axis parallel to the z-axis, and it collimates each of the illumination light components of the respective wavelengths emitted from the three corresponding point light sources of the illumination light source section 20, into a parallel plane wave and makes the parallel plane waves incident from mutually different incident directions to the spatial light modulator 30. In a case where the lens 20 is comprised of a single convex lens, the spacing between each of the three point light sources and the lens 20 is equal to the focal length of

the lens 20. Since the three point light sources are located at the aforementioned positions, the blue illumination light component is normally incident to the spatial light modulator 30, while the illumination light components of red and green are obliquely incident to the spatial light modulator 30. The lens 20 is preferably an achromatic lens having an identical focal length for the wavelengths of the respective illumination light components.

[0124] The spatial light modulator 30 is a transmission type spatial light modulator having the discrete pixel structure, and sequentially presents holograms associated with the three respective wavelengths, in time series. These holograms may be amplitude holograms or phase holograms. Then the spatial light modulator 30 sequentially presents holograms associated with wavelengths at respective points of time, in synchronism with time-series sequential incidence of the illumination light components of the respective wavelengths from the lens 20. This results in sequentially outputting reproduced light components of the respective wavelengths in time series. Namely, the field sequential system is adopted for the spatial light modulator 30.

[0125] The lens 40 subjects each of the reproduced light components of the three wavelengths generated

from the holograms presented on the spatial light modulator 30, to wavefront transformation onto the plane of mask 50. In a case where the lens 40 is comprised of a single convex lens, the spacing between the lens 40 and the mask 50 is equal to the focal length of the lens 40. The lens 40 is preferably an achromatic lens having an identical focal length for the wavelengths of the respective illumination light components.

[0126] The mask 50 is provided on the focal plane of the lens 40 and has an aperture 51. This aperture 51 has a rectangular shape each side of which is parallel to the x-axis or to the y-axis, and has a function of selecting only diffracted waves of a specific order generated from the spatial light modulator 30, a function of blocking nth-order directly transmitted light from the spatial light modulator 30, and a function of blocking unwanted light of components of nth-order diffracted waves which are generated from the holograms presented on the spatial light modulator 30 and which form a real image or a conjugate image to cause the problem of double images. The nth-order directly transmitted light from the spatial light modulator 30 is light contributing to image formation of the light sources as condensed by the lens 40, and becomes background light of a reproduced image to



degrade contrast. The aperture 51 is located in an area in which diffracted waves of any order out of the reproduced light components of the three wavelengths are superimposed on each other after the wavefront transformation by the lens 40. Particularly, in the present embodiment, the aperture 51 is provided in the area where the zero-order diffracted wave of the blue reproduced light component of the shortest wavelength and higher-order diffracted waves of the reproduced light components of the other two wavelengths are superimposed on each other after subjected to wavefront transformation by the lens 40. In this manner, the incident directions of the respective illumination light components of the three wavelengths to the spatial light modulator 30 are set by the illumination optical system.

[0127] The zero-order transmitted light having passed through the spatial light modulator 30 among the illumination light component emitted from the blue point light source at the location  $B(0,0)$  in the illumination light source section 10 is converged at the position  $B'(0,0)$  on the plane of mask 50 by the lens 40. The zero-order transmitted light having passed through the spatial light modulator 30 among the illumination light component emitted from the red point light source at the position  $R(x_r,0)$  or  $R(0,y_r)$  in the

illumination light source section 10 is converged at the position  $R'(x_r', 0)$  or  $R'(0, y_r')$  on the plane of mask 50 by the lens 40. The zero-order transmitted light having passed through the spatial light modulator 30 among the illumination light component emitted from the blue point light source at the position  $G(x_g, 0)$  in the illumination light source section 10 is converged at the position  $G'(x_g', 0)$  on the plane of mask 50 by the lens 40.

[0128] However, since the spatial light modulator 30 has the discrete pixel structure, as shown in Fig. 31 or Fig. 32, the image formation of the blue point light source on the plane of mask 50 obtains the wavefront transformation of the zero-order diffracted wave at the position  $G_1$ , the wavefront transformation of the first-order diffracted wave at each of eight positions  $G_2$  a distance  $(\lambda_b f/P)$  apart in the direction of the x-axis or the y-axis from the position  $G_1$ , and the wavefront transformation of higher-order diffracted waves at positions the distance  $(\lambda_b f/P)$  each further apart in the direction of the x-axis or the y-axis. The same also applies to the image formation of the point light sources of red and green. This will be detailed with reference to Fig. 33.

[0129] Fig. 33 is an illustration for explaining the spatial light modulator 30 and the reproduced image

transforming optical system of the 3D image display apparatus 4 according to the fourth embodiment. Let  $P$  be the pixel pitch of the spatial light modulator 30,  $\lambda_b$  be the wavelength of the blue illumination light component normally incident to the spatial light modulator 30,  $n_b$  be the order of the blue diffracted wave emerging from the spatial light modulator 30, and  $\theta_o$  be the emergence angle of the  $n_b$ th diffracted wave of blue from the spatial light modulator 30.

[0130] In this case, a relation given by Eq (16) below holds among these parameters.

$$P \sin \theta_o = n_b \lambda_b \quad \cdots (16)$$

[0131] From this Eq (16), the emergence angle  $\theta_o$  of the blue  $n_b$ th-order diffracted wave from the spatial light modulator 30 is expressed by Eq (17) below.

$$\theta_o = \sin^{-1}(n_b \lambda_b / P) \quad \cdots (17)$$

[0132] The blue  $n_b$ th-order diffracted wave from the spatial light modulator 30 is converged at the position the distance  $A_n$  apart from the optical axis, on the rear focal plane of lens 40 (the plane of mask 50). This distance  $A_n$  is represented by Eq (18) below.

$$\begin{aligned} A_n &= f_2 \tan \theta_o \\ &= f_2 \tan \{ \sin^{-1}(n_b \lambda_b / P) \} \\ &= f_2 \tan \{ \sin^{-1}(n_b \lambda_b / P) \} / \cos \{ \sin^{-1}(n_b \lambda_b / P) \} \end{aligned} \quad \cdots (18)$$

$$=(f_2 n_b \lambda_b / P) \cos\{\sin^{-1}(n_b \lambda_b / P)\}$$

[0133] As far as the order  $n_b$  is small, this Eq (18) is approximated by Eq (19) below.

$$A_n = f_2 n_b \lambda_b / P \quad \dots (19)$$

5 [0134] As seen from these Eq (18) or Eq (19), points of convergence of the zero-order and higher-order diffracted waves appear at almost equal intervals on the rear focal plane of lens 40 (plane of mask 50), and the appearance intervals of the convergence points of diffracted waves of respective orders are different depending upon the wavelength. Supposing the point light sources of the respective wavelengths in the illumination light source section 10 are present at the same position, the convergence points of the zero-order diffracted waves of the reproduced light components of the respective wavelengths appear at the same position, but the convergence points of the higher-order diffracted waves of the reproduced light components of the respective wavelengths appear at different positions, on the rear focal plane of lens 40 (plane of mask 50).

[0135] The diffracted waves forming a 3D reproduced image can be extracted by using the mask 50 with the aperture 51 based on the position expressed by above Eq (18) or Eq (19) and letting only diffracted

waves of any order out of the reproduced light components pass through the aperture 51. In a case where the spatial light modulator 30 is able to modulate both the amplitude and phase, the diffracted waves forming the 3D reproduced image can be extracted by placing the aperture 51 of rectangular shape having the length of  $f_2\lambda_b/P$  on one side with the center at the position expressed by above Eq (18) or Eq (19). In a case where the spatial light modulator 30 is able to modulate only one of the amplitude and phase, the diffracted waves forming the 3D reproduced image can be extracted by placing the aperture 51 of rectangular shape having the length of  $f_2\lambda_b/P$  on one side and the length of  $f_2\lambda_b/2P$  on the other side, on the half plane based on the position expressed by above Eq (18) or Eq (19) (a region corresponding to the hologram presentation area on the spatial light modulator 30).

[0136] In the present embodiment, concerning the aperture 51 of the mask 50, its area is not controlled in time division for each wavelength, but is constant independent of the wavelengths. Then the mask 51 placed herein is one having the location and shape adapted to  $\lambda_b$  being the shortest wavelength out of the three wavelengths ( $\lambda_r$ ,  $\lambda_g$ ,  $\lambda_b$ ). As for the other two wavelengths ( $\lambda_r$ ,  $\lambda_g$ ), the incident directions of the illumination light components to the spatial light

modulator 30 are set so that their diffracted waves of any order out of the reproduced light components pass through the aperture 51. Where the spatial light modulator 30 is able to modulate only one of the amplitude and phase, the convergence points of reproduced waves of the orders used in formation of the 3D image out of the reproduced light components of the respective wavelengths are made coincident with each other, whereby these convergence points are blocked by the mask 50. The lenses 20, 40 suitably applicable herein are lenses adequately compensated for chromatic aberration and having an identical focal length for each of the three wavelengths ( $\lambda_r$ ,  $\lambda_g$ ,  $\lambda_b$ ).

[0137] The blue illumination light component is normally incident to the spatial light modulator 30, while the other illumination light components of red and green each are obliquely incident thereto. The convergence point of the zero-order diffracted wave upon the normal incidence of the blue illumination light component must coincide with the convergence points of the higher-order diffracted waves of the specific order upon the oblique incidence of the other color illumination light components on the rear focal plane of lens 40. Angles of incidence of the illumination light components satisfying this condition will be described below with reference to Fig. 34.

[0138] Fig. 34 is an illustration for explaining the relation between the angle of incidence of an illumination light component and the angle of emergence of a reproduced light component in the spatial light modulator 30 of the 3D image display apparatus 4 according to the fourth embodiment. It is assumed that a parallel plane wave of any one wavelength  $\lambda_i$  ( $= \lambda_r$  or  $\lambda_g$ ) other than the shortest wavelength  $\lambda_b$  is incident at an incidence angle  $\theta_i$  to the spatial light modulator 30 and that the diffracted wave of order  $n_i$  among the reproduced light component of the wavelength  $\lambda_i$  is emergent at a diffraction angle  $\theta_o$  (the same as the blue diffracted wave is) from the spatial light modulator 30. The pixel pitch of the spatial light modulator 30 is assumed to be  $P$ .

[0139] In this case, a relation given by Eq (20) below holds among these parameters.

$$P \sin \theta_o - P \sin \theta_i = n_i \lambda_i \quad \dots (20)$$

[0140] Rewriting this into an equation for the incidence angle  $\theta_i$ , it is expressed by Eq (21) below.

$$\theta_i = \sin^{-1} \{ (P \sin \theta_o - n_i \lambda_i) / P \} \quad \dots (21)$$

[0141] By substituting aforementioned Eq (17), this Eq (21) is expressed by Eq (22) below.

$$\theta_i = \sin^{-1} \{ (n_b \lambda_b - n_i \lambda_i) / P \} \quad \dots (22)$$

[0142] When the blue illumination light component of wavelength  $\lambda_b$  is normally incident to the spatial light modulator 30 and when the illumination light component of the wavelength  $\lambda_i$  ( $= \lambda_r$  or  $\lambda_g$ ) is obliquely incident at the incidence angle  $\theta_i$  represented by above Eq (22), to the spatial light modulator 30, the diffracted waves of any order among the reproduced light components of the respective wavelengths are emergent at the same diffraction angle  $\theta_0$  from the spatial light modulator 30 to be converged at the same point by the lens 40.

[0143] From above Eq (20), the incidence angle  $\theta_i$  and the emergence angle  $\theta_0$  are equal to each other only when the diffraction order  $n_i$  is the zero order. The zero-order diffracted wave is converged at the position the distance  $A_{ni}$  expressed by Eq (23) below, apart from the optical axis on the rear focal plane of lens 40.

$$\begin{aligned} A_{ni} &= f_2 \tan \theta_i \\ &= f_2 \tan \left[ \sin^{-1} \{ (n_b \lambda_b - n_i \lambda_i) / P \} \right] \\ &= f_2 \tan \left[ \sin^{-1} \{ n_b \lambda_b / P \} \right] \\ &= f_2 (n_b \lambda_b / P) / \cos^{-1} \{ \sin(n_b \lambda_b / P) \} \end{aligned} \quad \dots (23)$$

As a first example about the distance  $A_{ni}$ , let us suppose that the order  $n_b$  of the diffracted wave of the blue wavelength  $\lambda_b$  is 0 and that the order  $n_i$  of the



diffracted wave of the other wavelength  $\lambda_i$  is -1. In this case, the incidence angle  $\theta_i$  of the illumination light component of the wavelength  $\lambda_i$  is represented by Eq (24) below.

$$\theta_i = \sin^{-1}(\lambda_i / P) \quad \dots (24)$$

[0144] The zero-order diffracted wave of the wavelength  $\lambda_i$  is converged at the position the distance  $A_{-1}$  represented by Eq (25) below, apart from the optical axis on the rear focal plane of lens 40.

$$\begin{aligned} A_{-1} &= f_2 \tan \theta_i \\ &= f_2 \tan[\sin^{-1}(\lambda_i / P)] \quad \dots (25) \\ &\cong f_2 \lambda_i / P \end{aligned}$$

[0145] As a second example about the distance  $A_{n1}$ , let us suppose that the order  $n_b$  of the diffracted wave of the blue wavelength  $\lambda_b$  is 0 and that the order  $n_i$  of the diffracted wave of the other wavelength  $\lambda_i$  is +1. In this case, the incidence angle  $\theta_i$  of the illumination light component of the wavelength  $\lambda_i$  is expressed by Eq (26) below.

$$\theta_i = \sin^{-1}(-\lambda_i / P) \quad \dots (26)$$

[0146] The zero-order diffracted wave of the wavelength  $\lambda_i$  is converged at the position the distance  $A_{+1}$  represented by Eq (27) below, apart from the optical axis on the rear focal plane of lens 40.

$$\begin{aligned}
A_{-1} &= f_2 \tan \theta_i \\
&= f_2 \tan [\sin^{-1}(-\lambda_i / P)] \quad \dots (27) \\
&\cong -f_2 \lambda_i / P
\end{aligned}$$

[0147] The illumination light component of the wavelength  $\lambda_i$  can be made incident as a parallel plane wave at the incidence angle  $\theta_i$  to the spatial light modulator 30 by placing the point light source at the position the distance  $B_{ni}$  represented by Eq (28) below, apart from the optical axis on the front focal plane of the lens 20 having the focal length  $f_1$ .

$$\begin{aligned}
B_{ni} &= -f_1 \tan \theta_i \\
&= -f_1 \tan [\sin^{-1} \{ (n_b \lambda_b - n_i \lambda_i) / P \}] \quad \dots (28)
\end{aligned}$$

[0148] As a first example about the distance  $B_{ni}$ , let us suppose that the order  $n_b$  of the diffracted wave of the blue wavelength  $\lambda_b$  is 0 and that the order  $n_i$  of the diffracted wave of the other wavelength  $\lambda_i$  is -1. In this case, the point light source of the wavelength  $\lambda_i$  is placed at the position the distance  $B_{-1}$  represented by Eq (29) below, apart from the optical axis on the front focal plane of lens 20.

$$\begin{aligned}
B_{-1} &= -f_1 \tan \theta_i \\
&= -f_1 \tan [\sin^{-1}(\lambda_i / P)] \quad \dots (29) \\
&\cong -f_1 \lambda_i / P \\
&= A_{-1} / M
\end{aligned}$$

[0149] Here  $M$  is the magnification of the optical system expressed by Eq (13).

[0150] As a second example about the distance  $B_{ni}$ , let us suppose that the order  $n_b$  of the diffracted wave of the blue wavelength  $\lambda_b$  is 0 and that the order  $n_i$  of the diffracted wave of the other wavelength  $\lambda_i$  is +1. In this case, the point light source of the wavelength  $\lambda_i$  is placed at the position the distance  $B_{+1}$  represented by Eq (30) below, apart from the optical axis on the front focal plane of lens 20.

$$\begin{aligned}
 B_{+1} &= -f_1 \tan \theta_i \\
 &= -f_1 \tan [\sin^{-1}(-\lambda_i / P)] \\
 &\cong f_1 \lambda_i / P \\
 &= -A_{-1} / M
 \end{aligned}
 \quad \dots (30)$$

[0151] Fig. 31 is an example in which on the front focal plane of lens 20 the red point light source is placed at the position  $(-f_1 \lambda_r / P, 0)$ , the green point light source at the position  $(+f_1 \lambda_g / P, 0)$ , and the blue point light source at the position  $(0, 0)$  and in which on the rear focal plane of lens 40 the -1st-order diffracted wave among the red reproduced light component, the +1st-order diffracted wave among the green reproduced light component, and the zero-order diffracted wave among the blue reproduced light component are converged at their respective convergence points coincident on the optical axis. Fig. 32 is an

example in which on the front focal plane of lens 20 the red point light source is placed at the position  $(0, -f_1\lambda_r/P)$ , the green point light source at the position  $(+f_1\lambda_g/P, 0)$ , and the blue point light source at the position  $(0, 0)$  and in which on the rear focal plane of lens 40 the -1st-order diffracted wave among the red reproduced light component, the +1st-order diffracted wave among the green reproduced light component, and the zero-order diffracted wave among the blue reproduced light component are converged at their respective convergence points coincident on the optical axis.

[0152] The holograms associated with the respective colors, presented on the spatial light modulator 30, are holograms upon normal incidence of the illumination light components of the respective colors to the spatial light modulator 30 and thus there is no need for concern about the incidence angles as described in the first embodiment, thus enabling simple and fast computation.

[0153] Next, a specific example of the fourth embodiment will be described. The spatial light modulator 30 used herein was a data projection liquid crystal panel LCX023AL (pixel pitch  $P = 26 \mu\text{m}$ ) available from Sony Corp. The lens 20 was an achromatic lens having the focal length of 150 mm, and

the lens 40 an achromatic lens having the focal length of 150 mm. The monochromatic light source 11<sub>r</sub> for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions 1.0 (L) × 0.5 (W) × 0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source 11<sub>g</sub> for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source 11<sub>b</sub> for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0154] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (-3.75 mm, 0) or at the position (0, -3.75 mm) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (+3.06 mm, 0). The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150 μm. The incidence angle of the red illumination light component to the spatial light modulator 30 was set at +1.43°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at -1.17°. The size of the aperture 51 of the mask 50 was 2.7 mm (W) × 1.3 mm (H). The drive frequency of the spatial light modulator 30 was 70 Hz,

the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

[0155] In the case where the zero-order diffracted wave of the blue reproduced light component is observed while the higher-order diffracted waves of the other color reproduced light components are observed, as in the present embodiment, the quantity of light of the higher-order diffracted waves is smaller than that of the zero-order diffracted wave. In order to increase the aperture efficiency, it is thus preferable to use as the spatial light modulator 30 a liquid crystal panel with macro lenses mounted for respective pixels. This results in diverging light passing through each pixel and increasing the light quantity of the higher-order diffracted waves. A liquid crystal panel LCX023CMT (pixel pitch  $P = 26 \mu\text{m}$ ) available from Sony Corp. can be used as the liquid crystal panel of this type. The color balance of color 3D images was improved by using this liquid crystal panel and adjusting the magnitude of drive currents supplied to the respective monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>,

and 11<sub>b</sub>.

[0156] As described above, the 3D image display apparatus 4 and 3D image display method according to the fourth embodiment are able to provide color display of a clear 3D image even with use of the spatial light modulator 30 of a low resolution, because the incident directions are appropriately set for the respective illumination light components of the three wavelengths incident to the spatial light modulator 30 and the zero-order diffracted wave or higher-order diffracted waves of the reproduced light components of the three wavelengths generated from the spatial light modulator 30 are superimposed on each other in the aperture 51 after the wavefront transformation by the lens 40. In addition, there is no need for the half mirror for superimposing the reproduced light components of the three wavelengths as required in the second conventional technology, nor for the high-speed shutter as required in the third conventional technology, and thus the present embodiment successfully provides the compact and inexpensive 3D image display apparatus.

(Fifth Embodiment)

[0157] Next, the fifth embodiment of the 3D image display apparatus and 3D image display method according to the present invention will be described. Fig. 35 is an illustration showing a configuration of the 3D image

display apparatus 5 according to the fifth embodiment. The 3D image display apparatus 5 shown in this figure has an illumination light source section 10, a lens 20, a half mirror 25, a reflection type spatial light modulator 30, a lens 40, and a mask 50. The illumination light source section 10, lens 20, and half mirror 25 constitute an illumination optical system for converting each of illumination light components of three wavelengths into a parallel plane wave and making the parallel plane waves incident from mutually different incident directions to the spatial light modulator 30. The half mirror 25 and the lens 40 constitute a reproduced image transforming optical system for subjecting each of reproduced light components of the three wavelengths generated from holograms presented on the spatial light modulator 30, to wavefront transformation into a virtual image or a real image. The illumination optical system and the reproduced image transforming optical system share the half mirror 25.

[0158] When compared with the fourth embodiment, the 3D image display apparatus 5 and 3D image display method according to the fifth embodiment are similar thereto in each of the illumination light source section 10, lens 20, lens 40, and mask 50, but are different therefrom in mutual arrangement of the



components due to the spatial light modulator 30 being the reflection type spatial light modulator. When compared with the fourth embodiment, the operation of the 3D image display apparatus 5, and the 3D image display method according to the fifth embodiment are different therefrom in that each illumination light component, after converted into a parallel plane wave by the lens 20, passes through the half mirror 25 to enter the spatial light modulator 30, in that the reproduced light components emerge on the same side as the side where the illumination light components are incident to the spatial light modulator 30, and in that each reproduced light component is subjected to the wavefront transformation by the lens 40 after reflected by the half mirror 25. For the rest, the operation of the 3D image display apparatus 5, and the 3D image display method according to the fifth embodiment are theoretically similar to those in the fourth embodiment.

[0159] Next, a specific example of the fifth embodiment will be described. The spatial light modulator 30 used herein was a reflection type liquid crystal panel MD800G6 for micro monitor (pixel pitch  $P = 12.55 \mu\text{m}$ ) available from Micro Display Corp. The lens 20 was an achromatic lens having the focal length of 120 mm, and the lens 40 an achromatic lens having

the focal length of 60 mm. The monochromatic light source 11<sub>r</sub> for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions 1.0 (L) × 0.5 (W) × 0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source 11<sub>g</sub> for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source 11<sub>b</sub> for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L) × 0.6 (W) × 1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0160] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (-6.24 mm, 0) or at the position (0, -6.24 mm) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (+5.09 mm, 0). The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150 μm. The incidence angle of the red illumination light component to the spatial light modulator 30 was set at +2.98°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at -2.43°. The size of the aperture 51 of the mask 50 was 2.2 mm (W) × 1.1 mm (H). The drive frequency of the spatial light modulator 30 was 90 Hz, the holograms associated with the respective colors

(wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

(Sixth Embodiment)

[0161] Next, the sixth embodiment of the 3D image display apparatus and 3D image display method according to the present invention will be described. Fig. 36 is an illustration showing a configuration of the 3D image display apparatus 6 according to the sixth embodiment. The 3D image display apparatus 6 shown in this figure has an illumination light source section 10, a half mirror 25, a lens 20, a reflection type spatial light modulator 30, and a mask 50. The illumination light source section 10, half mirror 25, and lens 20 constitute an illumination optical system for converting each of illumination light components of three wavelengths into a parallel plane wave and making the parallel plane waves incident from mutually different incident directions to the spatial light modulator 30. The lens 20 and the half mirror 25 constitute a reproduced image transforming optical system for subjecting each of reproduced light components of the three wavelengths generated from

holograms presented on the spatial light modulator 30,  
to wavefront transformation into a virtual image or a  
real image. The illumination optical system and the  
reproduced image transforming optical system share the  
5 lens 20 and the half mirror 25.

[0162] When compared with the fourth embodiment,  
the 3D image display apparatus 6 and 3D image display  
method according to the sixth embodiment are similar  
thereto in each of the illumination light source  
10 section 10, spatial light modulator 30, and mask 50,  
but are different therefrom in mutual arrangement of  
the components because of the spatial light modulator  
30 being the reflection type spatial light modulator.  
When compared with the case of the fourth embodiment,  
15 the operation of the 3D image display apparatus 6, and  
the 3D image display method according to the sixth  
embodiment are different therefrom in that the lens 20  
also acts as the lens 40, in that each illumination  
light component, after passing through the half mirror  
20 25, is converted into a parallel plane wave by the lens  
20 to enter the spatial light modulator 30, in that the  
reproduced light components emerge on the same side as  
the side where the illumination light components are  
incident to the spatial light modulator 30, and in that  
25 each reproduced light component is subjected to the  
wavefront transformation as reflected by the half

mirror 25 after passing through the lens 20. For the rest, the operation of the 3D image display apparatus 6, and the 3D image display method according to the sixth embodiment are theoretically almost similar to those in the fourth embodiment.

[0163] Next, a specific example of the sixth embodiment will be described. The spatial light modulator 30 used herein was a reflection type liquid crystal panel MD800G6 for micro monitor (pixel pitch  $P = 12.55 \mu\text{m}$ ) available from Micro Display Corp. The lens 20 also acting as the lens 40 was an achromatic lens having the focal length of 60 mm. The monochromatic light source 11<sub>r</sub> for emitting red light was a light emitting diode CL-280SR-C (wavelength 650 nm; dimensions 1.0 (L)  $\times$  0.5 (W)  $\times$  0.6 (H)) available from Citizen Electronics Co., Ltd. The monochromatic light source 11<sub>g</sub> for emitting green light was a light emitting diode E1S07-AG1A7-02 (wavelength 530 nm; dimensions 1.6 (L)  $\times$  0.6 (W)  $\times$  1.15 (H)) available from TOYODA GOSEI Co., Ltd. The monochromatic light source 11<sub>b</sub> for emitting blue light was a light emitting diode E1S07-AB1A7-02 (wavelength 470 nm; dimensions 1.6 (L)  $\times$  0.6 (W)  $\times$  1.15 (H)) available from TOYODA GOSEI Co., Ltd.

[0164] The monochromatic light source 11<sub>r</sub> for emitting red light was placed at the position (-3.02

mm, 0) or at the position (0, -3.02 mm) and the monochromatic light source 11<sub>g</sub> for emitting green light at the position (+2.54 mm, 0). The aperture diameter of each of the pinholes 12<sub>r</sub>, 12<sub>g</sub>, and 12<sub>b</sub> was 150  $\mu$ m.

5 The incidence angle of the red illumination light component to the spatial light modulator 30 was set at +2.98°, and the incidence angle of the green illumination light component to the spatial light modulator 30 at -2.43°. The size of the aperture 51 of  
10 the mask 50 was 2.2 mm (W)  $\times$  1.1 mm (H). The drive frequency of the spatial light modulator 30 was 90 Hz, the holograms associated with the respective colors (wavelengths) were sequentially presented on the spatial light modulator 30, and the three monochromatic  
15 light sources 11<sub>r</sub>, 11<sub>g</sub>, and 11<sub>b</sub> were sequentially activated in synchronism therewith, whereby a full-color 3D image was clearly observed through the aperture 51 of the mask 50.

[0165] It is apparent that the present invention  
20 can be modified in various ways, from the above description of the present invention. It is noted that such modifications are not to be considered as departing from the spirit and scope of the present invention but all improvements obvious to those skilled  
25 in the art are to be included in the scope of claims which will follow.

**Industrial Applicability**

[0166] According to the present invention, the spatial light modulator having the discrete pixel structure presents the holograms associated with the respective wavelengths. The illumination optical system converts each of the illumination light components of the respective wavelengths into a parallel plane wave and makes the parallel plane waves incident from the mutually different incident directions to the spatial light modulator. The reproduced image transforming optical system subjects each of the reproduced images of the wavelengths generated from the holograms presented on the spatial light modulator, to wavefront transformation into a virtual image or a real image. The mask with the aperture is provided on the focal plane of the optical system. Then the illumination optical system sets the incident directions of the respective illumination light components of the wavelengths to the spatial light modulator so that the diffracted waves of any order of the respective reproduced light components of the wavelengths are superimposed on each other in the aperture by the reproduced image transforming optical system. This configuration permits provision of the compact and inexpensive 3D image display apparatus and others capable of providing the color display of the

clear 3D image even with use of the spatial light  
modulator of a low resolution.